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Direct and indirect loss of natural area from urban expansion

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Global losses of natural area are primarily attributed to cropland expansion, while the role of urban expansion is considered minor. However, urban expansion can induce cropland displacement, potentially leading to a loss of forests elsewhere. The extent of this effect is unknown. This study shows that indirect forest losses, through cropland displacement, far exceed direct losses from urban expansion. On a global scale, urban land increased from 33.2 to 71.3 Mha between 1992 and 2015, leading to a direct loss of 3.3 Mha of forests, and an indirect loss of 17.8 – 32.4 Mha. In addition, this urban expansion led to a direct loss of 4.6 Mha of shrublands, and an indirect loss of 7.0 – 17.4 Mha. Guiding urban development towards more sustainable trajectories can thus help preserve forests and other natural areas at a global scale.

The global competition for land between multiple uses has led to a dramatic loss of natural areas[1]. This loss of natural areas has had large and negative impacts on terrestrial biodiversity[2] ecosystem services[3], and the loss of forests in particular has also greatly contributed to global greenhouse gas emissions[4]. Expansion of agricultural land has been identified as the most important proximate cause of the loss of natural areas[5,6]. As a consequence, agricultural intensification and dietary changes have received much attention as potential solutions to reduce the decline of natural areas[7–9].

Contrary to agricultural expansion, urban development is only associated with a small fraction of all forest losses[5,6]. Although the relationship between urbanization and forest loss has been firmly established, the underlying mechanism that relates urbanization and forest loss is not clear[10]. Land use displacement, i.e. the geographic displacement of land use activities[11], can potentially explain this relationship. The conversion of cropland into urban land and the development of new cropland elsewhere to compensate for the loss in production can be interpreted as land use displacement. As urban expansion often takes place in cropland areas[12], and as cropland expansion often leads to a conversion of natural areas[6,13], cropland displacement can relate urban expansion to losses of natural areas elsewhere. Future land use change scenarios have projected this effect at both local[14] and global[15] scales, but to date there has been no analysis of observed changes.

This paper analyses to what extent urban expansion has contributed directly but also indirectly to the loss of natural areas between 1992 and 2015. Direct changes refer to natural areas that converted into urban land, while indirect changes refer to natural areas that converted into cropland to compensate for cropland that converted into urban land elsewhere. In other words, indirect changes are a consequence of cropland displacement. Natural areas considered in this study include forests and shrubland, but exclude grassland, because it was not possible to differentiate between managed grassland and natural grassland. The analyses test the hypothesis that indirect losses of natural area exceed direct losses. The analyses also tests the hypothesis that differences in cropland productivity leverage cropland displacement, i.e. that the area of cropland that is required to compensate for the loss in crop production is larger than the area of cropland that converted into urban land. Both hypotheses build on the observation that urban areas are typically located in highly productive agricultural regions[12], while new cropland mainly comes at the cost of forests and other natural areas[13] .

Results

Direct land cover changes. According to the ESA-CCI land cover data[16] 38.0 Mha of new urban land appeared globally between 1992 and 2015 (Fig. 1c), representing a 115% increase in only 23 years. About 64% of this urban expansion took place on former cropland, while 9%, 13% and 10% led to a direct loss of forests, shrubland, and grassland, respectively (Fig. 1a and Suppl. Tab. 1). The remaining 5% led to a conversion of other land, which mainly constitutes bare land. Yet, large differences exist between world regions. For example, more than 75% of the urban expansion in Southeast Asia, India, China, and Europe took place on former cropland areas, while this was 40% or less in Oceania, Sub-Saharan Africa, and the Middle East and Northern Africa (MENA). Consistently, in regions where most urban expansion took place on cropland, little urban expansion took place on forests and shrubland, and vice versa (Fig 1a and Suppl. Tab. 1).

Analysis of the same data also shows that new cropland mostly leads to a conversion of forests (56%) and shrubland (30%), while 11% and 3% led to a conversion of grassland and other land, respectively (Fig. 1b and Suppl. Tab. 2). At a regional scale, large differences exist in land cover types that change into cropland, mainly related to the prevailing natural vegetation in different regions. For example, cropland expansion in Southeast Asia and Latin America mainly lead to a loss of forests, while cropland expansion in Oceania and MENA mainly led to a loss in shrubland. In some regions, notably China, Russia and Central Asia, and Sub-Saharan Africa, there was a considerable amount of grassland that converted into cropland.

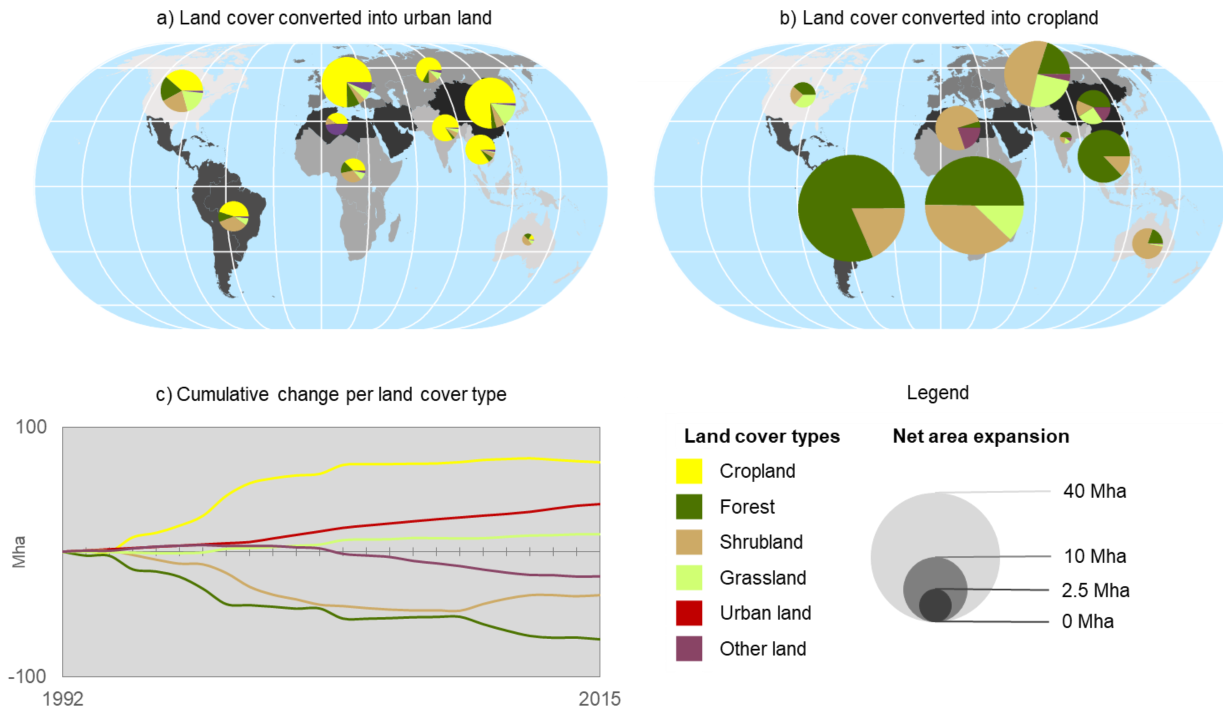

Figure 1: *Observed land cover changes between 1992 and 2015. Figures 1a and 1b show land cover changes as a result of urban expansion and cropland expansion, respectively, for ten world regions included in this study. Regions are shown in the background in different shades of grey, and in more detail in Suppl. Fig. 1. Pie charts are scaled according to net area increase in both classes between 1992 and 2015. Note that there was a net decrease in cropland in Europe, hence no pie is depicted. Fig. 1c shows the cumulative net change for each of the six major land cover types at a global level.*

Cropland displacement and indirect land cover change. Urban expansion between 1992 and 2015 led to a direct loss of 3.3 Mha of forest and 4.6 Mha of shrubland (Tab. 1). In addition, urban expansion led to a loss of 24.3 Mha of cropland, producing the equivalent of 122 Mton of cereals per year (Tab 2.). The amount of new cropland required to compensate for this loss in production depends on where this new cropland is developed, as cropland productivity differs between regions. Under the assumption that cropland displacement takes place within the same region, urban expansion led to 32.5 Mha of displaced cropland, globally (Suppl. Tab. 3). Under the assumption that cropland displacement takes place across all regions, urban expansion led to 58.0 Mha of displaced cropland, globally (Suppl. Tab. 4). Consistently, the loss of forests and shrubland as a result of cropland displacement also depends on where cropland is displaced to, because the percentage of new cropland resulting in a conversion of forests and shrublands differs between regions. Under the assumption that cropland displacement takes place within the same region, urban expansion led to 17.8 Mha of indirect forest loss and 7.0 Mha of indirect shrubland loss, while the remaining 7.6 Mha of displaced cropland led to a conversion of grassland and other land (Tab 3. and Suppl Tab. 3). Under the assumption that cropland displacement takes place across all regions, urban expansion led to 32.4 Mha of indirect forest loss and 17.4 Mha of indirect shrubland loss, while the remaining 8.2 Mha of displaced cropland led to a conversion of grassland and other land (Tab. 3 and Suppl. Tab. 4).

Table 1: *Direct land cover change as a result of urban land expansion between 1992 and 2015. MENA indicates Middle East and Northern Africa.*

Region	Urban expansion [Mha]	Direct land cover change due to urban expansion [Mha]				
		Forest	Shrubland	Cropland	Grassland	Other land
Canada and USA	6.1	1.2	1.4	2.3	1.2	0.1
China	8.8	0.2	0.5	6.7	1.2	0.1
Europe	8.4	0.7	0.9	6.3	0.5	0.5
India	2.4	0.1	0.2	2.0	0.1	0.0
Latin America	3.1	0.3	0.5	1.4	0.2	0.1
MENA	1.6	0.0	0.0	0.7	0.0	0.8
Oceania	0.5	0.1	0.1	0.1	0.1	0.0
Russia and Central Asia	2.2	0.2	0.3	1.5	0.2	0.1
Southeast Asia	3.0	0.2	0.2	2.5	0.0	0.1
Sub-Saharan Africa	1.9	0.3	0.5	0.7	0.2	0.1
World total	38.0	3.3	4.6	24.3	3.7	1.9

The ratio between the productivity of cropland converted into urban land and the productivity of new cropland required to compensate for this loss can be interpreted as a leverage factor. A leverage factor higher than 1 indicates that the cropland converted into urban land had a higher productivity than the displaced cropland. This means that the area of new cropland required to compensate for the loss in crop production is higher than the amount of cropland area that is converted in urban land. Conversely, a leverage factor lower than 1 indicates that the cropland converted into urban land has a lower productivity than the new and displaced cropland, which means that the area of new cropland required to compensate for the loss in crop production is lower than the amount of cropland area that is converted in urban land.

Table 2: *Loss of crop production due to urban expansion and new cropland required to compensate for this loss between 1992 and 2015 under different assumptions of cropland displacement. Leverage factors indicate the ration between the productivity of cropland converted into urban land and the productivity of new cropland required to compensate for this loss.*

Region	Loss of crop production due to urban expansion [Mton]	Cropland required to compensate [Mha]		Leverage factor [-]	
		Within region displacement	Across region displacement	Within region displacement	Across region displacement
Canada and USA	10.4	3.2	4.9	1.37	2.10
China	54.2	10.7	25.7	1.61	3.85
Europe	27.3	13.1	13.0	2.08	2.06
India	7.1	2.9	3.4	1.43	1.65
Latin America	3.3	1.6	1.5	1.13	1.11
MENA	1.0	0.7	0.5	1.10	0.74
Oceania	0.1	0.1	0.1	0.90	0.69
Russia and Central Asia	2.4	2.5	1.2	1.64	0.77
Southeast Asia	15.2	7.0	7.2	2.77	2.85
Sub-Saharan Africa	1.1	1.0	0.5	1.29	0.68
World total	122.1	32.5	58.0	1.34	2.39

The assumption that cropland is displaced within the same world region leads to a leverage factor of 1.34 for all world regions together (Tab. 2). In other words, the area of new cropland that is required to compensate for the loss in crop production is 34% higher than the area of cropland that is lost to urbanization. Yet, leverage factors differ considerably between regions, ranging from 0.90 in Oceania to 2.77 for Southeast Asia. This means that new cropland in Oceania is more productive than cropland converted into urban land in Oceania, while new cropland in Southeast Asia is much less productive than cropland that converted into urban land in that region. The assumption that crop production lost to urban expansion is compensated across all world regions leads to a global leverage factor of 2.39 (Tab. 2). This means that the area of new cropland that is required to compensate for the loss in crop production is 139% higher than the area of cropland that is lost to urbanization, for all world regions combined. On a regional level, a leverage factor of, for example, 2.06 for Europe means that the average productivity of cropland converted into urban land in Europe is 106% higher than the average productivity of all new croplands, globally

The effect of displacement within regions vis-à-vis displacement across regions differs between world regions. For India, for example, the leverage factor for displacement within the same region is 1.43 and the leverage factor for displacement across region is 1.65 (Tab. 2). Thus, both assumptions lead to a leverage factor larger than 1, thus indicating a leverage effect. In Russia and Central Asia, on the other hand, cropland displacement within the same region leads to a leverage factor of 1.64 while cropland displacement across regions leads to a leverage factor of 0.77. This means that cropland converted into urban land in Russia and Central Asia is on average 64% more productive than new cropland developed in the same region, but it is 23% less productive than new cropland developed in other regions. Globally, cropland displacement across all world regions leads to a higher leverage factor and thus to a higher indirect loss of forest and shrubland than displacement within world regions. The difference is caused by a high amount of urban expansion in regions with relatively high cropland productivity, such as China and Canada and USA, in combination with a high amount of cropland expansion in regions with relatively low average productivity, such as Sub-Saharan Africa, and Latin America (Fig. 2). Because it is not possible to trace where exactly cropland is displaced to, results of both assumptions can be interpreted as boundary values of the range of plausible results (Tab. 3).

Table 3: *Indirect loss land cover changes as a result of cropland displacement due to urban expansion between 1992 and 2015 under different assumptions of cropland displacement. Values indicate the indirect land cover change related to urban expansion in the respective regions.*

Region	Indirect forest loss [Mha]		Indirect shrubland loss [Mha]		Indirect grassland loss [Mha]		Indirect loss of other land [Mha]	
	Within region displacement	Across region displacement	Within region displacement	Across region displacement	Within region displacement	Across region displacement	Within region displacement	Across region displacement
Canada and USA	1.3	2.7	0.8	1.5	1.2	0.5	0.0	0.2
China	5.3	14.1	1.9	7.6	2.7	2.7	1.7	0.9
Europe	7.9	7.1	3.4	3.8	1.3	1.4	0.4	0.5
India	1.3	1.9	0.7	1.0	0.5	0.4	0.3	0.1
Latin America	1.1	0.8	0.3	0.5	0.0	0.2	0.0	0.1
MENA	0.0	0.3	0.5	0.1	0.0	0.1	0.1	0.0
Oceania	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Russia and Central Asia	0.5	0.6	1.2	0.3	0.6	0.1	0.1	0.0

Southeast Asia	5.0	4.0	0.7	2.1	0.0	0.8	0.0	0.3
Sub-Saharan Africa	0.5	0.3	0.4	0.1	0.1	0.1	0.0	0.0
World total	17.1	31.8	7.0	17.1	5.3	6.2	2.3	2.0

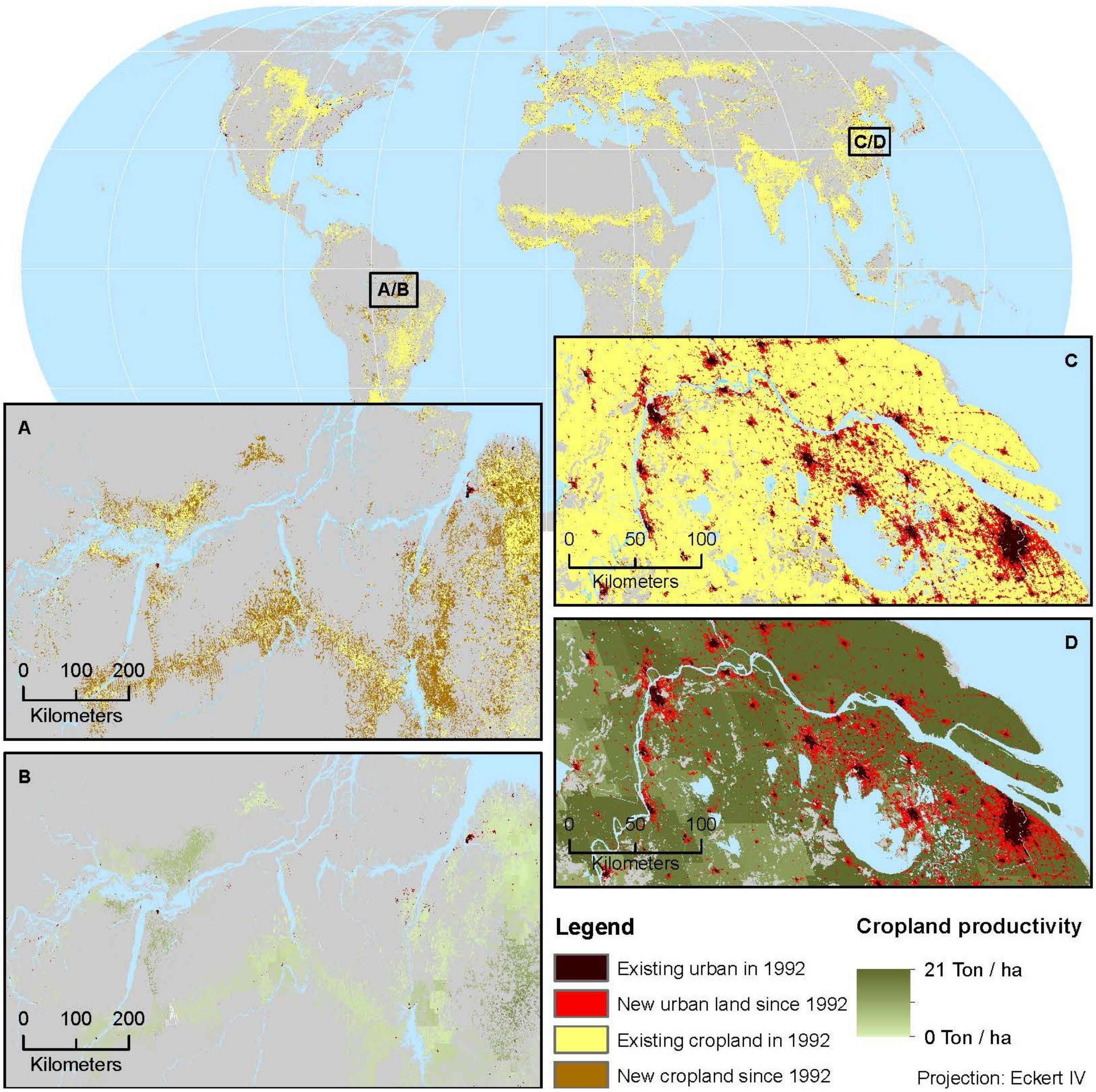

Figure 2: *Urban expansion and cropland expansion between 1992 and 2015. A-D show close-ups of two typical but contrasting areas in terms of observed land use change and the cropland productivity in these areas. Map A depicts part of the amazon basin, characterized by a large amount of cropland expansion between 1992 and 2015, which is characterized by a low cropland productivity (Map B). Map C shows Shanghai and the southern part of Jiangsu province in China, which has experienced a large amount of urban expansion between 1992 and 2015, mostly on highly productive cropland (Map D).*

Impact of land use management. To assess to what extent the leverage factor of cropland displacement is caused by differences in land use management and to what extent it is a result of different biophysical properties, the same analyses were repeated using potential yields instead of actual yields. Based on potential yields, the amount of displaced cropland decreases slightly, to 28.0 Mha for displacement within world regions and 41.7 Mha for displacement across all regions (Suppl. Tab. 5 and 6). Consequently, leverage factors for cropland displacement based on potential yield decrease to 1.15 – 1.72, as compared to 1.34 – 2.39 based on actual yields, on a global level. These numbers result in an indirect loss of 14.9 – 23.3 Mha of forest and 6.1 – 12.5 Mha of shrubland (Suppl. Tab. 5 and 6 and Fig. 3). The lower and upper bound of these values indicate cropland displacement within and across regions, respectively. Thus, when accounting for differences in land use management the leverage effect in cropland displacement remains, and indirect losses of forest and shrubland still exceed the direct losses by a large margin (Fig. 3).

Crops cultivated in newly developed cropland areas are not necessarily the same as the crops previously cultivated in areas converted into urban land. To account for these differences in crop mixes, the analysis was repeated based on the caloric values of the produce of a larger group of 16 different crop types. These crops include wheat, maize and rice, but also crops that are often associated with (tropical) deforestation such as oil palm and soybean. Using actual yields, 29.8 – 43.7 Mha of new cropland are required to compensate for the lost production due to urban expansion, leading to a leverage factor of 1.23 – 1.80 (Suppl. Tab. 7 and 8). This leads to 15.0 – 24.4 Mha of indirect forest loss and 6.8 – 13.1 Mha of indirect shrubland loss (Suppl. Tab. 7 and 8, and Fig. 3). Using potential yields instead of actual yields to calculate caloric productivity decreases the leverage factor to 1.11 – 1.49, globally, leading to 13.6 – 20.3 Mha of indirect forest loss and 6.0 – 10.9 Mha of indirect shrubland loss (Fig. 3, Suppl. Tab. 9 and 10). Accounting for differences in cultivated crops thus results in lower leverage factors than the analysis based on major cereal crops only, but these leverage factors remain larger than 1. Moreover, indirect forest and shrubland losses also remain much higher than direct losses when accounting for different crop types (Fig. 3).

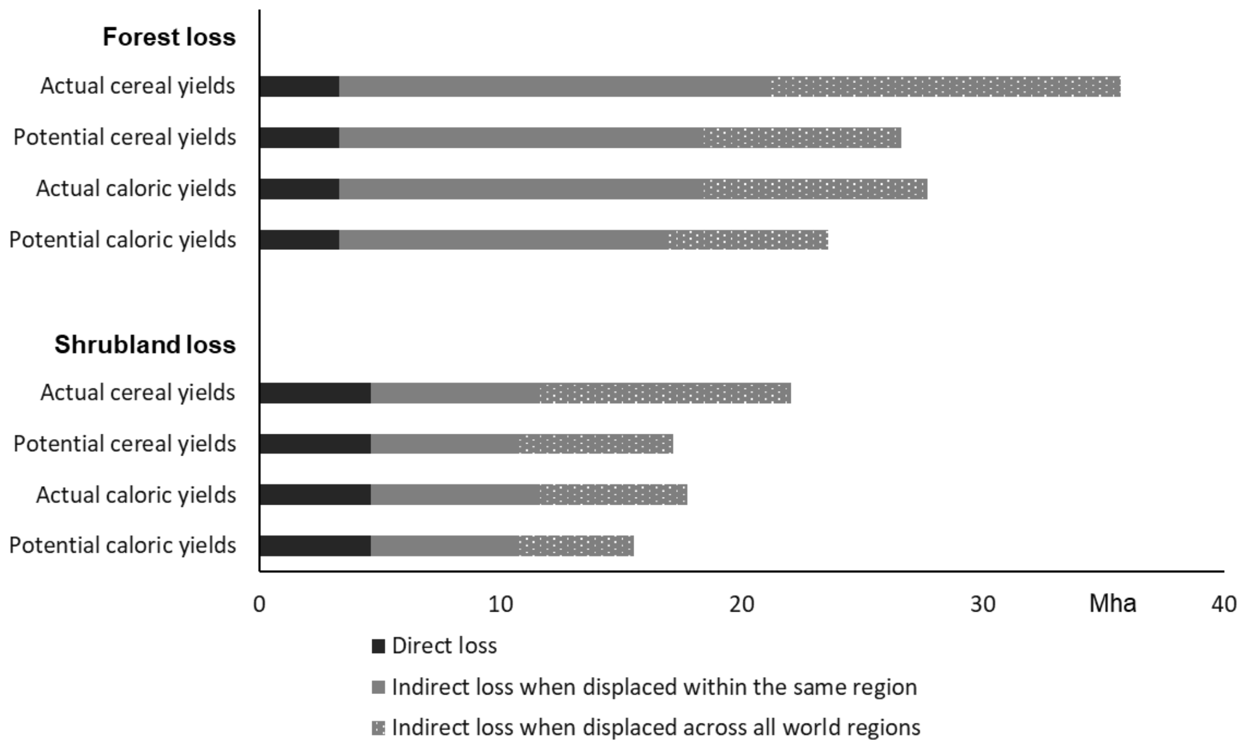

Figure 3: *Direct and indirect losses of forests and shrubland under different assumptions for cropland displacement.*

Discussion

This study analyses the direct and indirect losses of forest and shrubland due to urban expansion, where indirect losses are a consequence of cropland displacement. Results show that urban expansion mostly leads to a direct loss of cropland, and new cropland mostly leads to a conversion of forests and shrubland elsewhere. As a result, indirect losses of forest and shrubland due to urban expansion are much higher than direct losses, confirming this hypothesis. Results also confirm the hypothesis that cropland displacement is leveraged by the differences in productivity of lost cropland and new cropland areas. Different assumptions for cropland displacement and cropland productivity affect the strength of the leverage effect and thus the size of indirect land cover changes, but both hypotheses remain confirmed under all assumptions used.

Urban expansion also lead to a conversion of grasslands. However, the global land cover data used does not differentiate between managed grasslands (i.e. pastures) and natural grasslands. When urban expansion leads to a conversion of natural grasslands, these conversions would further add to the direct losses of natural area. When, on the other hand, urban expansion leads to a conversion of pastures, this could lead to pasture displacement. Such displacement would further add to the indirect losses of natural areas from urban expansion, given the important role of pasture expansion in deforestation, especially in the Amazon[17,18]. As a consequence, both the direct and the indirect losses of natural areas from urban expansion are likely higher than reported here based on the displacement of cropland only.

Between 1992 and 2015, the total urban expansion was equal to 38.0 Mha, an area slightly larger than the land area of Japan. This change corresponds to an increase in urban land of 1.66 Mha per year. Two recently presented global datasets present yearly increases of urban land of 1.19 Mha per year between 1975 and 2014[19] and 1.49 Mha per year between 1990 and 2010[20]. As both of these datasets only present the absence and presence of built-up land, and no other land cover classes, it is not possible to assess to what extent those differences would affect the results presented in this study. Comparisons of global maps of urban land indicate that differences arise due to different definitions, as well as different data sources, but that these differences are distributed equally over all world regions[21,22]. Therefore, differences between estimates will likely affect the size of the direct and indirect land cover change, but it is unlikely to change the main findings of this paper that indirect changes exceed direct changes, and that this effect is leveraged by differences in cropland productivity.

Few studies have previously assessed the future impacts of indirect land changes resulting from urban expansion at local[14] and global[15] scales. The global assessment[15] projected a displacement of almost 65 Mton of crop production, corresponding to between 6.7 and 35 Mha of new cropland between 2000 and 2040. Based on the same quantification of crop production (actual yields of wheat, maize, and rice), the present study finds 122 Mton of crop displacement corresponding to 32.5 – 58.0 Mha of new cropland in only 23 years. The difference between the previous study and the present study relates to the amount of urban expansion and the productivity of cropland areas. As the present study is based on empirical data, rather than model-based projections, this comparison suggests that the cropland displacement and indirect losses in forests and natural areas until 2040 could far exceed the previously presented simulation results.

Leverage from cropland displacement. Global agricultural trade has increased in recent decades[23] especially between more affluent countries, where the majority of the urban expansion has taken place, and developing countries, where most of the new cropland is located[24]. China is a prime example of the process analyzed in this study, as it has experienced the largest amount of urban expansion of all regions between 1992 and 2015, while the import of cropland products into China has increased rapidly in recent decades[25]. Because most urban expansion has taken place in developed regions with higher cropland productivity (See also Fig. 2C-D), and because most cropland expansion has taken place in developing countries with lower cropland productivity (See also Fig 2A-B), the leverage effect is likely to be on the higher side of the values presented for all regions combined.

The difference between the productivity of cropland converted to urban land and the productivity of new cropland is a result of both biophysical suitability of locations and land management practices[26]. As land use intensity is typically higher around urban areas and lower in more remote areas[12], differences in land use management could affect the leverage effect in cropland displacement. Based on actual yields, cropland displacement within the same region requires ~~on average~~ 34% more land than what was converted into urban land. Based on potential yields, cropland displacement within the same region requires ~~on average~~ 15% more land than what was converted into urban land. The 19 percent points difference between actual and potential yields can thus be attributed to land management. Similarly, based on actual yields, cropland displacement across all regions requires ~~on average~~ 139% more land than what was converted into urban land. Based on potential yields, cropland displacement across all regions requires ~~on average~~ 72% more land than what was converted into urban land. The 67 percent point difference can thus be attributed to land management. In other words, land use management and biophysical suitability each have roughly similar impact on the leverage effect of cropland displacement.

Land use intensification could also take place in existing croplands that are not affected by urban expansion, although spatially explicit data about this intensification is not available[27]. Yet, a recent review found that cropland expansion in forest frontiers is often market-driven, while management intensification is more often fueled by technological development[28]. This suggests that losses in crop production from urban expansion mainly lead to the development of new croplands, as is assumed in the present study. In addition, cropland losses could increase the price for crop products, because they increase land rents for remaining cropland areas and thus prices for crop products produced in these remaining areas. This increase in price could lead to a decrease in the demand for crop products. However, price elasticities for agricultural commodities are low[29] and the loss in crop production due to urban expansion is small relative to the total crop production on a global scale. Therefore, this study assumes that these effects do not alter total demand for crop products and that all crop production lost to urban expansion is displaced elsewhere.

Crops associated with (tropical) deforestation are not necessarily the same crops that are cultivated on cropland converted into urban land. For example, oil palm is often associated with deforestation in tropical areas[30,31], while it is hardly found in areas with urban expansion. Another example is the rapid expansion of soybean cultivation, such as in the Gran Chaco in Argentina and in other areas in the Neo-tropics [32,33]. However, accounting for differences in crop mixes hardly changes the leverage effect nor the indirect losses in forests and shrublands as a result of cropland displacement. Hence, this finding reinforces the confirmation of both hypotheses tested in this study, and indicates that the results are not due to specific crop types

Implications. Urban areas are expected to continue expanding in the next decades[34,35], and recent projections indicate this expansion can severely impact food production[36] as well as natural areas[37]. This expected urban expansion offers a window of opportunity to guide urban development trajectories in order to minimize environmental impact. Solutions to reduce the competition for land often focus on agricultural production[7,8,26], while the potential for more efficient use of urban areas is hardly explored.

Results of this study suggest that both the location and the total area of urban expansion provide opportunities to reduce the competition for land. Instead of converting fertile croplands, urban development could be directed towards less productive areas. Because urban areas are increasingly decoupled from their agricultural resource base[38], such allocation decisions can now be made without compromising their functionality much. The *Economic and intensive land use policy* in China is a step in this direction as it aims to protect specifically the most fertile croplands against urban expansion[39]. Additionally, a focus on urban densification could reduce the amount of urban expansion. Currently, large differences exist in the population densities of cities across different continents[34,40], indicating there is room to reduce the built-up land area per person in many world regions. Few countries, mainly in China and Europe, have already introduced policies that promote compact cities or reduce urban sprawl in order to steer urban development trajectories towards reducing their environmental impact[41,42]. At the same time, examples from USA and Australia show that not all planning initiatives towards compact development have been effective[43,44]. Urban planning outcomes in the Global South are further challenged by conflicting realities, i.e. between rationalities of governments and administrations on one side, and realities of survival of the poor and often marginalized population on the other[45]. Moreover, compact development has to be balanced against other dimensions of sustainable urbanization in order to preserve the livability of cities for their inhabitants[46].

Land use and land use change are pivotal in many sustainability challenges, and model-based assessments are elementary in analyzing possible solutions[47,48]. Yet, the representation of urban systems in land use models is rather simplistic, in contrast to the modelling of agricultural and natural land systems[49,50]. As a consequence, the potential of alternative urban development trajectories to mitigate direct and indirect land cover change, as well as related environmental impacts, remains to be investigated.

Methods

This study calculates direct and indirect changes in forest areas and shrubland areas as a result of urban expansion. Direct changes refer to the conversion of forests and shrublands into urban land. Indirect changes refer to the conversion of forests and shrublands into cropland, in order to compensate for the conversion of cropland into urban land elsewhere. In other words, indirect changes are the result of cropland displacement. Changes in land cover and crop production are analyzed at the pixel level and subsequently aggregated to the scale of ten world regions separately (Canada and USA, China, Europe, India, Latin America, Middle-east and Northern Africa (MENA), Oceania, Russia and Central Asia, Southeast Asia and Sub-Saharan Africa) as well as the entire world. Aggregation to regions is needed in order to relate pixels where cropland converted into urban land to other pixels where new cropland appeared and thus calculate cropland displacement from urban expansion.

Regions in this analysis are delineated based on the standard regions as used by the World Bank, with the notable exception of East Asia and Pacific and Europe and Central Asia. These regions are further subdivided to reflect the differences in both urban expansion and agricultural trade dynamics. Specifically, East Asia and Pacific was further subdivided into China, Southeast Asia, and Oceania. This subdivision follows analyses of agricultural trade-flows[24,51], indicating that China is increasingly importing cropland products, while Southeast Asia is a major source of these cropland products [24,25,52]. Similarly, Europe was separated from Russia and Central Asia because Europe has experienced a large amount of urban expansion, while this development was much less strong in Russia and Central Asia. As a result, regions represent relatively coherent groups of countries, for which the majority of the crop products consumed are also produced within that region[51], justifying the assumption of within-region displacement. At the same time, these regions also represent the regions that form the sending and receiving side of the rapidly increasing amount of global trade in crop products. Regions are depicted in Suppl. Fig. 1.

Land cover change analysis. Land cover changes between 1992 and 2015 are based on ESA-CCI Land Cover data, which provides land cover maps for all years between 1992 to 2015[16]. Land cover data in this dataset is derived from multiple different sensors and presented at a ~ 300 meter resolution (depending on the latitude)[53]. All land cover maps were reclassified into six aggregate classes (Cropland, Forest, Urban land, Shrubland, Grassland, and Other). Mosaic classes in the ESA-CCI data were reclassified into combinations of the aggregated classes according to the shares of the respective plant functional types found in these mosaic classes[54]. Urban land in this study corresponds with the class *urban areas* in the ESA-CCI map. The classification of the ESA-CCI follows the UN Land Cover Classification System (LCCS)[55] which defines urban areas as "primarily non-vegetated areas with an artificial cover resulting from human activities"[56]. The complete reclassification scheme is presented in Suppl. Tab. 11. Reclassified land cover maps were combined with an area-grid to account for different cell sizes to find the total area for each land cover and for each year.

Land cover maps for the years 1992 and 2015 were overlaid to derive a land cover change map, indicating for each pixel the land cover at the start and at the end of the study period. This land cover change map was also combined with an area-grid to obtain the total area per land cover change type between 1992 and 2015. All pixels that were either forest or shrubland in 1992 and changed into urban land in 2015 were considered direct land cover changes as a result of urban expansion, and their area was calculated accordingly.

Quantification of cropland displacement. To calculate cropland displacement, the total crop production of pixels converted into urban land was calculated and used to compute the equivalent amount of newly developed cropland required to produce the same amount of crops. Both new cropland and cropland converted into urban land are derived from the land cover change between 1992 and 2015. Crop production, rather than cropland area, was used for this analysis to account for the differences in productivity in different locations. To compare pixels with different crop types, a representative productivity was calculated for each pixel, which is the productivity that would be obtained when all harvested area is covered with wheat, maize or rice, proportional to the actual occurrence of wheat, maize and rice in that location. Together these three cereal crops represent about 65% of all harvested area globally, and at least one of these three crops can be found in the vast majority of all cropland areas around the world. Therefore, and because their yields under favorable conditions is comparable, this operationalization of productivity was deemed suitable to calculate cropland displacement[57,58].

The representative productivity (tons produce per hectare of cropland) is calculated at a 5 arcminute resolution by multiplying the average yield of wheat, maize and rice (tons per hectare of harvested area) with the multi-cropping factor in each pixel. The average yield is calculated as the area-weighted average of the yields of these three crops, where areas refer to the harvested area of each of these three crops in that pixel. The multi-cropping factor is calculated as the total harvested area of all 175 crops covered in Monfreda *et al.*[59] in a pixel divided by the cropland area in that same pixel as reported in Ramankutty et al.[60]. Yields for wheat, maize and rice are taken from Mueller et al.[61], which provides data for around the year 2000. This yield data is an updated yet consistent version of the yields presented in Monfreda *et al.*[59], and thus is also consistent with the calculation of the multi-cropping factor. Gaps in the spatial coverage, i.e. pixels for which no wheat, maize, or rice data was estimated in the Monfreda data, but for which either a cropland loss or cropland gain was reported in the ESA-CCI land cover data, are filled using a focal average (i.e. the average of all pixels directly and diagonally adjacent to this location). Any remaining gaps are not filled and instead these locations are excluded from the calculation of average productivity of cropland changes. These gaps comprise 2.4% of all cropland converted into urban land and in 1.9% of all new cropland areas. As these percentages are close, this decision is unlikely to yield any systematic bias towards either of these change types. After this data processing, productivity data is resampled to the resolution of the land cover maps using the a nearest neighbor assignment. Suppl. Tab. 12 provides more detail of all data used in this study.

Cropland displacement is calculated using two contrasting assumptions: either cropland is displaced within the same region, or cropland is displaced across all regions. In both cases, cropland displacement is calculated as the amount of cropland that is required to compensate for the loss in crop production due to urban expansion. For cropland displacement within a region, this is based on the average productivity of all new cropland that appeared within that same region between 1992 and 2015. For cropland displacement across all regions, this is based on the average productivity of all new cropland that appeared in all regions between 1992 and 2015. These two situations are reported as extreme values that bound the possibility space of cropland displacement.

For Europe it is not possible to completely compensate all lost crop production within the same region, because the amount of newly developed cropland between 1992 and 2015 was not large enough. Therefore, under the assumption of displacement within the region, the amount of crop production that could be compensated by new cropland in Europe is displaced within the region, while the additional crop production that could not be compensated within Europe is displaced across all other world regions.

Actual and potential yields. Analyses of cropland displacement are conducted for actual yields as well as for potential yields, based on data for around the year 2000[61] (Suppl. Tab. 12). Potential yield is defined here as the attainable yield after water and nutrient deficiencies have been removed, and serves as a way to separate the impact of land management from the inherent biophysical suitability of locations to produce crops. Results based on potential yield thus indicate cropland displacement if the newly developed land is managed with the same intensity as the cropland converted into urban land.

Newly developed cropland areas might differ from cropland converted into urban land in the mix of crops that is grown. These differences are not necessarily reflected in the average productivity of wheat, maize and rice. Therefore, the calculations are repeated using the actual and potential productivity of a larger number of crops, expressed in caloric value. This calculation is based on 16 food crops for which both actual and potential yield information was available from Mueller et al[61], i.e. wheat, rice, maize, soybean, barley, sorghum, millet, rapeseed, groundnut, sunflower, sugarcane, potato, cassava, oil palm, rye, and sugar beet. These crops coincide with the crop types used in earlier analysis of cropland losses from urban expansion[36]. Together these crops comprise 76% of all harvested area globally, including some of the crops that have been associated with deforestation in recent years, such as palm oil and soy beans[30,32]. The analysis based these 16 crops is otherwise similar to the analysis based on the productivity of three major cereal crops, in that a representative productivity is calculated based on the area-weighted average productivity of the crops included, except that productivity is expressed in Kcal, rather than tons of produce. Crop yields are converted into caloric values using standard nutritive values as reported for the different crops by the FAO[62].

Indirect loss of forest and shrubland. Displaced cropland as a result of urban expansion is multiplied by the percentage of new cropland leading to a loss of forests and shrubland, respectively, to calculate indirect losses for forests and shrubland. For cropland displacement within the region, these numbers indicate the percentage of new cropland leading to a conversion of forests and shrublands within that region. For cropland displacement across all regions, these numbers indicate the percentage of new cropland leading to a conversion of forests and shrublands in all regions. Consistent with the reporting of cropland displacement, indirect losses of forest and shrubland are reported as a range of values bound by the assumptions of displacement within the same region and displacement across all regions.

Leverage factors. To further express the impact of cropland displacement, a leverage effect is calculated as $P_{converted}/P_{new}$, where $P_{converted}$ is the average productivity of cropland converted into urban land, and P_{new} is the average productivity of new cropland areas that can be used to compensate for the loss in crop production. Values larger than 1 indicate that the area of cropland required to compensate for the lost production due to urban expansion exceeds the area of cropland that is lost, while values below 1 indicate the opposite. Indirect losses of forest are subsequently calculated based on the amount of displaced cropland and the share of new cropland leading to conversion of forest. Similarly, indirect losses of shrubland are calculated based on the amount of displaced cropland and the share of new cropland leading to conversion of shrubland.

Implementation. The area of each cell in the ESA-CCI land cover maps was derived from the area() function of the 'raster' package in R. All other spatial analyses are implemented in Python, using spatial analysis functions from the ArcPy package. These spatial analyses provide results per world region. All spatial analysis results are post-processed in MS Excel. This post-processing includes combining regional results to obtain global-scale results.

Code availability. Scripts used for this analysis are available from the author upon reasonable request.

Data availability. Data that support the findings presented in this study are available from the author upon reasonable request.

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Author contributions

J.V. designed the study, conducted the data analysis, and wrote the paper.

Additional information

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